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(12) INTERNATIONAL APPLICATION PUBLISHED UNDER THE PATENT COOPERATION TREATY (PCT)

(19) World Intellectual Property Organization  
International Bureau



(43) International Publication Date  
19 April 2001 (19.04.2001)

PCT

(10) International Publication Number  
**WO 01/27690 A2**

- (51) International Patent Classification?: **G02F 1/15,**  
C09K 9/02
- (21) International Application Number: **PCT/IE00/00123**
- (22) International Filing Date: 11 October 2000 (11.10.2000)
- (25) Filing Language: English
- (26) Publication Language: English
- (30) Priority Data:  
S990846 11 October 1999 (11.10.1999) IE
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- (81) Designated States (national): AE, AG, AL, AM, AT, AU, AZ, BA, BB, BG, BR, BY, BZ, CA, CH, CN, CR, CU, CZ, DE, DK, DM, DZ, EE, ES, FI, GB, GD, GE, GH, GM, HR, HU, ID, IL, IN, IS, JP, KE, KG, KP, KR, KZ, LC, LK, LR, LS, LT, LU, LV, MA, MD, MG, MK, MN, MW, MX, MZ, NO, NZ, PL, PT, RO, RU, SD, SE, SG, SI, SK, SL, TJ, TM, TR, TT, TZ, UA, UG, US, UZ, VN, YU, ZA, ZW.
- (84) Designated States (regional): ARIPO patent (GH, GM, KE, LS, MW, MZ, SD, SL, SZ, TZ, UG, ZW), Eurasian patent (AM, AZ, BY, KG, KZ, MD, RU, TJ, TM), European patent (AT, BE, CH, CY, DE, DK, ES, FI, FR, GB, GR, IE, IT, LU, MC, NL, PT, SE), OAPI patent (BF, BJ, CF, CG, CI, CM, GA, GN, GW, ML, MR, NE, SN, TD, TG).
- Published:  
— Without international search report and to be republished upon receipt of that report.
- For two-letter codes and other abbreviations, refer to the "Guidance Notes on Codes and Abbreviations" appearing at the beginning of each regular issue of the PCT Gazette.



WO 01/27690 A2

(54) Title: **ELECTROCHROMIC DEVICE**

(57) Abstract: This invention concerns an electrochromic device comprising an electrode including a nanostructured metal oxide film, doped to metallic levels of conductivity and optionally modified by chemisorption of an electroactive compound. Such an electrochromic device is suitable for applications where optical modulation is required, such as large area static displays and automatically dimmable rear-view mirrors. The invention also concerns conducting nanostructured metal oxide films and electrodes comprising same and which are suitable for use in the electrochromic device.

# ELECTROCHROMIC DEVICE

This invention relates to an electrochromic device. In particular, it relates to a nanostructured metal oxide  
5 film, doped to metallic levels of conductivity and modified by chemisorption of an electroactive compound, an electrode comprising such a nanostructured film and an electrochromic device comprising such an electrode.

10 The use of electrochromic devices in applications where optical modulation is required, such as large area static displays and automatically dimmable rear-view mirrors, is well known. Electrochromic devices comprising at least one electrode incorporating a  
15 semiconducting nanostructured metal oxide film modified by chemisorption of an electroactive compound are also known, see for example WO-A-97/35227 and WO-A-98/35267.

The device disclosed in WO-A-97/35227 comprises an n-  
20 or p-type redox chromophore chemisorbed at the surface of a nanostructured semiconductor electrode, and an auxiliary electroactive compound of the p- or n-type, respectively, which can be oxidised or reduced in a reversible manner, is dissolved in the electrolyte. In  
25 the device disclosed in WO-A-98/35267 an n-type redox chromophore is chemisorbed at the surface of a nanostructured semiconductor electrode and a p-type redox promoter is dissolved in the electrolyte. Although the switching time of these devices is more  
30 rapid than that of previously known devices, it is still relatively slow due to the rate-limiting step being the diffusion of the electroactive compound in electrolyte to the relevant electrode. Attempts to eliminate this rate-determining step by adsorbing this  
35 compound to the electrode to which it diffuses have

only resulted in moderate increases in the rate of switching due to the semiconducting nature of the nanostructured substrate.

5 While the devices disclosed in WO-A-97/35227 and WO-A-98/35267 are adequate for the applications mentioned above, more rapid switching times would be desirable, especially where dynamic displays, privacy glazing and smart windows are concerned.

10 It is an object of the invention to avoid or minimise the disadvantages of the prior art. It is also an object of the invention to provide an electrochromic device having more rapid switching times than known  
15 devices.

According to the invention there is provided a nanoporous, nanocrystalline film comprising a conducting metal oxide having an electroactive compound  
20 which is either a p-type or n-type redox promoter or p-type or n-type redox chromophore adsorbed thereto.

A "nanocrystalline film" is constituted from fused nanometer-scale crystallites. To form a conducting  
25 film the crystallites are appropriately doped. In a "nanoporous, nanocrystalline" film the morphology of the fused nanocrystallites is such that it is porous on the nanometer-scale. Such films, which may hereinafter be referred to as (conducting/semiconducting)  
30 nanostructured films, typically possess a surface roughness of about 1000 assuming a thickness of about 3  $\mu\text{m}$ . Conducting nanostructured films have a resistance of 20 k $\Omega$ /square for a 3  $\mu\text{m}$  thick nanostructured Sb doped  $\text{SnO}_2$  film on a non-conducting  
35 substrate at room temperature.

As used herein the term "conducting metal oxide" refers to metal oxides suitably doped to a level that ensures their sheet resistance is less than 100 Kohms per square.

5

As used herein, the term "electroactive compound" refers to (1) those compounds which are adsorbed at the surface of a conducting nanostructured metal oxide film and are oxidised. If these compounds change colour on being oxidised, they are referred to as p-type redox chromophores. If they do not change colour, they are referred to as p-type redox promoters; and (2) those compounds which are adsorbed at the surface of a semiconducting or conducting nanostructured metal oxide film and are reduced. If these compounds change colour on being reduced, they are referred to as n-type redox chromophores. If they do not change colour, they are referred to as n-type redox promoters.

20 The invention also provides an electrode for use in an electrochromic device comprising a transparent or translucent substrate bearing an electrically conducting coating which in turn bears a conducting nanostructured metal oxide film according to the invention.

The invention further provides an electrochromic device comprising at least one electrode according to the invention.

30

The electrochromic device of the invention may comprise two electrodes, each comprising a conducting nanostructured metal oxide film according to the invention.

Thus, in one embodiment of the invention, the electrochromic device comprises:

- (a) a first electrode comprising a transparent or translucent substrate bearing an electrically conducting coating on its internal face which in turn bears a nanostructured film comprising a conducting metal oxide having an n-type or p-type redox chromophore or n-type or p-type redox promoter adsorbed thereto;
- (b) a second or counter electrode comprising a transparent or translucent substrate bearing an electrically conducting coating on its internal face which in turn bears a nanostructured film comprising a conducting metal oxide having a p-type or n-type redox promoter or p-type or n-type redox chromophore adsorbed thereto; and
- (c) an electrolyte intermediate the electrodes.

In a preferred embodiment, the electrochromic device according to the invention comprises:

- (a) a first electrode comprising a transparent or translucent substrate bearing an electrically conducting coating on its internal face which in turn bears a nanostructured film comprising a semiconducting metal oxide having an n-type redox chromophore adsorbed thereto;
- (b) a second or counter electrode comprising a transparent or translucent substrate bearing an electrically conducting coating on its internal face which in turn bears a nanostructured film comprising a

conducting metal oxide having a p-type redox promoter adsorbed thereto; and

(c) an electrolyte intermediate the electrodes.

5

Alternatively, a p-type redox chromophore may be adsorbed to the conducting metal oxide and an n-type redox promoter is then adsorbed to the semiconducting metal oxide.

10

In a particularly preferred embodiment of the electrochromic device of the invention, the first electrode is the cathode and the nanostructured film coated thereon comprises  $\text{TiO}_2$  having an n-type redox chromophore of the formula I, II or III (as defined hereinafter) adsorbed thereto; and the second electrode is the anode and the nanostructured film coated thereon comprises  $\text{SnO}_2:\text{Sb}$  having a p-type redox promoter of the formula IV, V, VI or VII (as defined hereinafter) adsorbed thereto.

20

In another aspect, the invention provides an electrochromic device comprising:

25 (a) a first electrode comprising a transparent or translucent substrate bearing an electrically conducting coating on its internal face which in turn bears a nanostructured film comprising a conducting or semiconducting metal oxide having an n-type or p-type redox chromophore adsorbed thereto;

30

(b) a second or counter electrode comprising a transparent or translucent substrate bearing an electrically conducting coating on its internal face which in turn bears a nanostructured film comprising a

35

conducting metal oxide without an electroactive compound adsorbed thereto; and

(c) an electrolyte intermediate the electrodes.

5

In this embodiment, the device will function as an electrochromic device due to the physical properties of the nanostructured film. Firstly, the material has the ability to release electrons and provide these for the  
10 reduction of the redox chromophore on the (semi)-conducting metal oxide electrode and secondly, due to the high roughness factor of the film, a large interface between the electrolyte and the film is maintained enabling efficient charge compensation  
15 within the device. In a device which has a smooth film, the performance would be less efficient.

In the electrochromic devices of the invention, the following provisos apply:

20

(1) where the metal oxide is a semiconducting metal oxide, an n-type electroactive compound is adsorbed thereto;

25 (2) where first and second electrodes both comprise electroactive compounds: (a) the first electrode comprises an n-type redox chromophore and the second electrode comprises a p-type redox promoter or vice versa; or (b) the first electrode comprises an n-type  
30 redox promoter and the second electrode comprises a p-type redox chromophore or vice versa; (a) and (b) being subject to proviso (1) above;

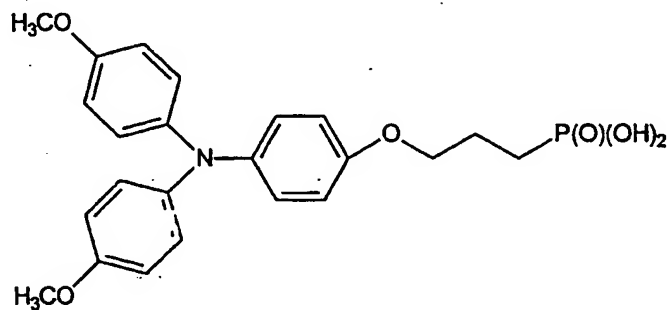
(3) where only one of the first and second electrodes  
35 comprises an electroactive compound, said compound is

an n-type or p-type redox chromophore, subject to proviso (1) above.

The electrodes in the electrochromic device of the invention are preferably spaced apart, for example by a distance of up to 5 mm, preferably at a distance of from 50  $\mu\text{m}$  to 5 mm.

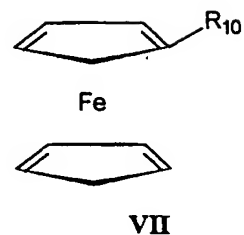
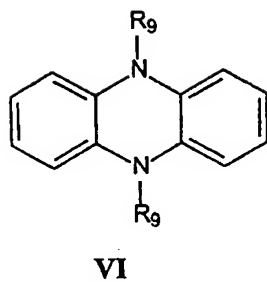
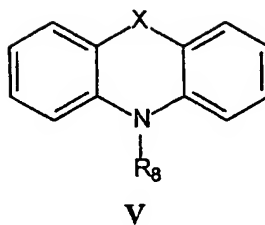
Any suitable n- or p-type redox promoters or redox chromophores may be used in the conducting nanostructured films of the present invention.

Preferred p-type redox promoters and redox chromophores are compounds of the following formulae IV - VII:

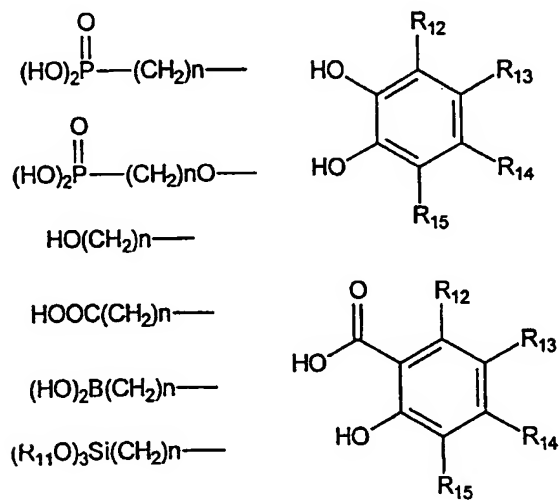


IV

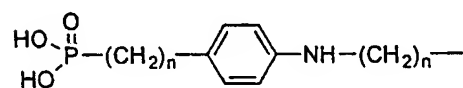
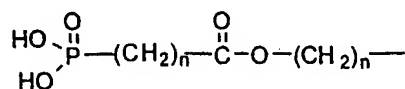




wherein X in formula V is S or O and  $R_8$ - $R_{10}$  are each independently selected from the following:



5



wherein  $R_{11}$  is  $C_{1-10}$  alkyl and  $R_{12}-R_{15}$  are each  
independently hydrogen;  $C_{1-10}$  alkyl;  $C_{1-10}$   
5 alkylene; optionally substituted aryl; halogen;  
nitro; or an alcohol group; and  $n = 1-10$ .

Compounds of the general formulae V, VI and VII are  
novel and form part of this invention, together with  
10 their use in the preparation of conducting  
nanostructured films, electrodes and electrochromic  
devices according to the invention.

The compound of the formula IV is known and may be  
15 prepared according to conventional procedures as  
described in *J. Am. Chem. Soc.* 1999, 121, 1324-1336.

Compounds of the general formula V can be prepared by  
reacting phenothiazine with an alkyl halide terminated  
20 with the precursor to or a suitable linker group.

Compounds of the general formula VI can be prepared by  
reacting an alkyl substituted dihydro-dialkyl phenazine  
with an alkyl halide terminated with the precursor to  
25 or a suitable linker group.

Compounds of the general formula VII can be prepared by  
reacting a suitably derivatized ferrocene with an alkyl  
halide terminated with the precursor to or a suitable  
30 linker group.

A particularly preferred p-type redox promoter of the  
general formula V is  $\beta$ -(10-phenothiazyl) propoxy

phosphonic acid. This compound (compound VIII) can be prepared according to reaction scheme 1 hereinafter.

The conducting metal oxide used in the nanostructured films of the present invention is preferably selected from any of the following:

- (a)  $\text{SnO}_2$  doped with F, Cl, Sb, P, As or B;
- (b)  $\text{ZnO}$  doped with Al, In, Ga, B, F, Si, Ge, Ti, Zr or Hf;
- (c)  $\text{In}_2\text{O}_3$  doped with Sn;
- (d)  $\text{CdO}$ ;
- (e) Ternary oxides such as  $\text{ZnSnO}_3$ ,  $\text{Zn}_2\text{In}_2\text{O}_5$ ,  $\text{In}_4\text{Sn}_3\text{O}_{12}$ ,  $\text{GaInO}_3$  or  $\text{MgIn}_2\text{O}_4$ ;
- (f)  $\text{Fe}_2\text{O}_3$  doped with Sb;
- (g)  $\text{TiO}_2/\text{WO}_3$  or  $\text{TiO}_2/\text{MoO}_3$  systems; and
- (h)  $\text{Fe}_2\text{O}_3/\text{Sb}$  or  $\text{SnO}_2/\text{Sb}$  systems.

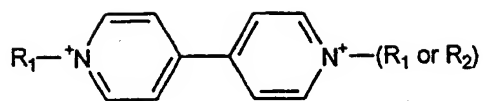
$\text{SnO}_2$  doped with Sb is particularly preferred.

20

Preferred semiconducting metal oxides which may be used in an electrochromic device of the invention are oxides of titanium, zirconium, hafnium, chromium, molybdenum, tungsten, vanadium, niobium, tantalum, silver, zinc, strontium, iron ( $\text{Fe}^{2+}$  or  $\text{Fe}^{3+}$ ) or nickel or a perovskite thereof.  $\text{TiO}_2$ ,  $\text{WO}_3$ ,  $\text{MoO}_3$ ,  $\text{ZnO}$  and  $\text{SnO}_2$  are particularly preferred.

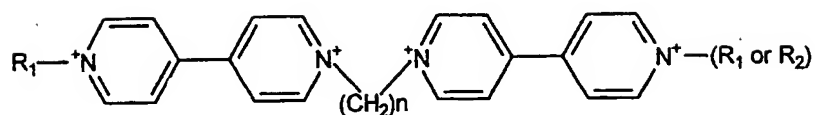
Preferred n-type redox chromophores or redox promoters which may be used in an electrochromic device of the present invention are compounds of the following general formulae I-III:

30



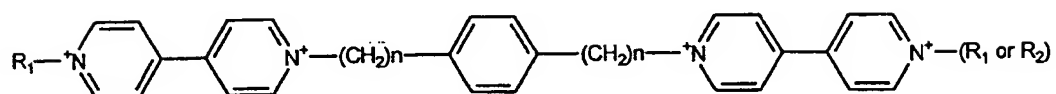
2X

I



4X

II

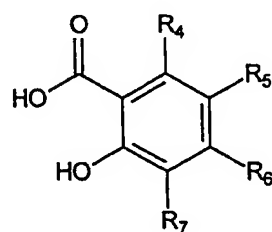
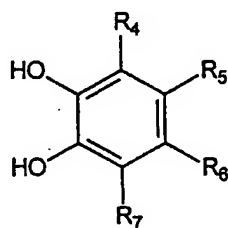
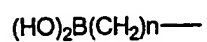
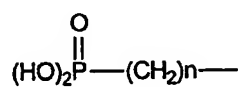


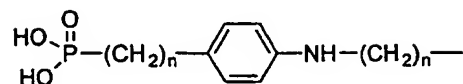
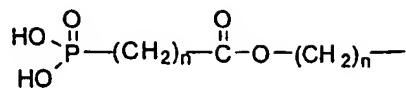
4X

III

5

wherein  $R_1$  is selected from any of the following:





5

$R_2$  is selected from  $C_{1-10}$  alkyl, N-oxide, dimethylamino, acetonitrile, benzyl and phenyl optionally mono- or di-substituted by nitro;

10

$R_3$  is  $C_{1-10}$  alkyl and  $R_4-R_7$  are each independently selected from hydrogen;  $C_{1-10}$  alkyl;  $C_{1-10}$  alkylene; aryl or substituted aryl; halogen; nitro; and an alcohol group;

15

X is a charge balancing ion which is preferably selected from chloride, bromide, iodide,  $\text{BF}_4^-$ ,  $\text{PF}_6^-$ , and  $\text{ClO}_4^-$ ; and  $n = 1-10$ .

20

Compounds of the formulae I, II and III are known and may be prepared in known manner as described in *Solar Energy Materials and Solar Cells*, 57, (1999), 107-125.

25

A particularly preferred n-type redox chromophore for use in the present invention is a compound of formula I, viz. bis-(2-phosphonoethyl)-4,4'-bipyridinium dichloride.

30

The conducting and semiconducting metal oxide films may be treated by exposure to a water plasma stream prior to adsorption of the electroactive compounds. Such treatment is useful in promoting reaction of the linker groups, especially siloxane groups, of the

electroactive compounds with the hydroxyl groups on the surface of the metal oxide films as it increases the concentration of the latter groups. This treatment also increases the stability of the nanostructured  
5 films.

The electrode substrates are suitably formed from a glass or plastics material. Glass coated with a conducting layer of fluorine doped tin oxide or indium  
10 tin oxide is conveniently used in an electrochromic device of the present invention.

The electrolyte used in the present invention is preferably in liquid form and preferably comprises at  
15 least one electrochemically inert salt in solution in a solvent. Examples of suitable salts include lithium salts, such as lithium perchlorate ( $\text{LiClO}_4$ ), lithium tetrafluoroborate ( $\text{LiBF}_4$ ), lithium iodide ( $\text{LiI}$ ), lithium hexafluorophosphate ( $\text{LiPF}_6$ ), lithium hexafluoroarsenate  
20 ( $\text{LiAsF}_6$ ), lithium styrylsulfonate ( $\text{LiSS}$ ), lithium triflate ( $\text{LiCF}_3\text{SO}_3$ ), lithium methacrylate, lithium halides other than  $\text{LiI}$ , such as lithium chloride ( $\text{LiCl}$ ), lithium bromide ( $\text{LiBr}$ ) and the like, lithium trifluoroacetate ( $\text{CF}_3\text{COOLi}$ ) and combinations thereof.  
25 Of these,  $\text{LiClO}_4$  or combinations of  $\text{LiClO}_4$  and  $\text{LiBF}_4$  are preferred. These sources of alkali metal ions may be present in the electrolyte in a concentration of about 0.01M to 1.0M, with a concentration of about 0.05M to 0.2M being preferred.

30

Suitable solvents may be selected from acetonitrile, 3-hydroxypropionitrile, methoxypropionitrile, 3-ethoxypropionitrile, 2-acetylbutyrolactone, propylene carbonate, ethylene carbonate, glycerine carbonate,  
35 tetramethylene sulfone, cyanoethyl sucrose,

$\gamma$ -butyrolactone, 2-methylglutaronitrile,  
N,N'-dimethylformamide, 3-methylsulfolane,  
glutaronitrile, 3,3'-oxydipropionitrile, methylethyl  
ketone, cyclopentanone, cyclohexanone, benzoyl acetone,  
5 4-hydroxy-4-methyl-2-pentanone, acetophenone, 2-  
methoxyethyl ether, triethylene glycol dimethyl ether,  
4-ethenyl-1,3-dioxalane-2-one, 1,2-butylene carbonate,  
glycidyl ether carbonates (such as those commercially  
available from Texaco Chemical Company, Austin, Texas)  
10 and combinations thereof, preferred of which include  $\gamma$ -  
butyrolactone, propylene carbonate, 1,2-butylene  
carbonate, the combination of tetramethylene sulfone  
and propylene carbonate and the combination of 1,2-  
butylene carbonate and propylene carbonate.  
15  $\gamma$ -Butyrolactone is particularly preferred.

The use of a conducting nanostructured substrate in the  
electrochromic device of the present invention having a  
p-type redox promoter or redox chromophore adsorbed  
20 thereto, greatly increases the rate of electron  
transfer from the adsorbed p-type redox promoter or  
redox chromophore to the positively biased substrate.  
Consequently, the switching speed of the electrochromic  
device is greatly increased. Furthermore, the  
25 advantages of an adsorbed p-type redox promoter or  
redox chromophore, namely low power consumption and  
extended memory, are maintained

The invention is illustrated in the following Examples.  
30

#### EXAMPLE 1

(a) A 2.5 cm x 2.5 cm transparent nanostructured  
semiconductor film, consisting of a 4  $\mu$ m thick layer of

fused  $\text{TiO}_2$  nanocrystallites, was deposited on a 3.3 cm x 3.3 cm fluorine doped tin oxide on glass substrate (15  $\Omega$ , 0.5  $\mu\text{m}$  thick, Libby-Owen Ford Tec 15). A colloidal  $\text{TiO}_2$  dispersion was prepared by hydrolysis of titanium tetraisopropoxide. The average diameter of the initially formed crystallites (7 nm) was increased by autoclaving at 200°C for 12 hours to 12 nm. Concentrating the autoclaved dispersion to 160 g/l and adding Carbowax (Trade Mark) 20000 (40% wt. equiv. of  $\text{TiO}_2$ ) yielded a white viscous sol. (Carbowax 20000 is an ethylene glycol polymer whose average molecular weight is 20000.) A 4  $\mu\text{m}$  thick layer of the above sol was deposited using a screen printing technique on the conducting glass substrate. The resulting gel-film was dried in air for 1 h, sintered in air at 450°C for 12 h and stored in a darkened vacuum desiccator prior to use. The resulting transparent nanostructured electrodes were 4  $\mu\text{m}$  thick and had a surface roughness of about 1000.

20

(b) An n-type redox chromophore, bis-(2-phosphonoethyl)-4,4'-bipyridinium dichloride was prepared by adding 4,4'-bipyridine (4.4 g) and diethyl-2-ethylbromo-phosphonate (15.0 g) to water (75 ml). The reaction mixture was refluxed for 72 h and allowed to cool. Following addition of conc. hydrochloric acid (75 ml) the reaction mixture was refluxed for a further 24 h. To recover the product, the reaction mixture was concentrated to 50 ml, isopropyl alcohol (200 ml) added drop-wise, stirred on ice for one hour and filtered. The white crystalline product was washed with cold isopropyl alcohol and air dried to give pure bis-(2-phosphonoethyl)-4,4'-bipyridinium dichloride (12.72 g,

30



84.24 % yield). Calculated for bis-(2-phosphonoethyl)-4,4'-bipyridinium dichloride ( $C_{14}H_{20}N_2Cl_2O_6P_2$ ) :

C, 37.77; H, 4.53; N, 6.29. Found: C, 35.09; H, 4.49;

N, 6.09.  $^1H$  NMR (water- $d_2$ ):  $\delta$  2.31-2.43 (m, 4H);

5  $\delta$  4.68-4.80 (m, 4H);  $\delta$  8.33 (d, unresolved metacoupling, 4H);  $\delta$  8.94 (d, unresolved metacoupling, 4H).

(c)  $TiO_2$  films, prepared as described above, were  
10 modified by chemisorption of a monolayer of the n-type redox chromophore, also prepared as described above, from an aqueous solution ( $0.02 \text{ mol} \cdot \text{dm}^{-3}$ ) over 24 h, washed with distilled isopropanol, dried in air and stored in a darkened vacuum desiccator for 48 h prior  
15 to use.

(d) A 2.5 cm x 2.5 cm transparent nanostructured  $SnO_2:Sb$  film was prepared on a 3.3 cm x 3.3 cm F-doped tin oxide glass substrate ( $15 \Omega$ ,  $0.5 \mu\text{m}$  thick,  
20 supplied by Libby-Owen Ford Tec 15) largely as described in "*Spectroscopy of Highly Doped Nanostructured Tin Dioxide Electrodes*" The Journal of Physical Chemistry, 1999, 103, pp 3093-3098, G. Boschloo and D. Fitzmaurice. Briefly, 10 drops of  
25 acetic acid ( $2.0 \text{ mol} \cdot \text{dm}^{-3}$ ) were added with stirring to an aqueous dispersion (50 g) of 5 nm diameter Sb-doped  $SnO_2$  nanocrystals (15% by wt.  $SnO_2:Sb$ , supplied by Alfa). The gel which formed immediately was diluted by addition of water (15 ml) and autoclaved at  $200^\circ\text{C}$  for  
30 12 h. Addition of Carbowax 20000 (3.75 g) with stirring for 8 h yielded an amber viscous paste which was diluted with water (10 ml) to make it suitable for spreading. This paste was spread using a glass rod on

the conducting glass substrate masked by Scotch tape. Following drying in air for 1 h the film was fired, also in air, at 450°C for 12 h. The resulting transparent nanostructured SnO<sub>2</sub>:Sb films were 3.0 µm  
5 thick and had a surface roughness of about 1000.

(e) The p-type redox promoter VIII was prepared as shown in Scheme 1, as follows:

10 **XI:  $\beta$ -(10-phenothiazyl) propionitrile**

Triton B (benzyl trimethylammonium hydroxide; 0.6 ml of a 40% aq. soln.) was added dropwise to a solution of phenothiazine (X, 50 g) in acrylonitrile (45 ml) on ice resulting in a vigorous reaction. The reaction mixture  
15 was refluxed for 1 h and allowed to cool. The resulting crude product was recrystallized from a 30:70 mixture of hot ethanol and acetone to yield orange crystals of XI, (31.27 g, 49.6%).

20 **XII:  $\beta$ -(10-phenothiazyl) propionic acid**

The compound XI (31.27 g) was added to a mixed solvent (350 ml methanol, 105 ml water) NaOH (35 g) solution, refluxed for 15 h and allowed to cool. The crude product was poured on ice water and acidified by the  
25 addition of sulphuric acid (2 mol dm<sup>-3</sup>) until a white precipitate formed. The crude product was recrystallised to yield XII, (17.0 g, 52.26%).

**XIII:  $\beta$ -(10-phenothiazyl) propionate ester**

30 The compound XII (17 g) was dissolved in 1:2 by vol. mixture of ethanol and toluene (700 ml) acidified by addition of conc. sulphuric acid (4 ml) and refluxed overnight. The solution was concentrated (to

approximately 50 ml) and diluted by addition of water (500 ml). The crude product was extracted in ethyl acetate (4 x 200 ml), washed with water, dried over  $\text{MgSO}_4$ , filtered and the solvent removed under reduced pressure. White crystals of XIII precipitated from the solution on cooling, (11.85 g, 63.9%).

**XIV:  $\beta$ -(10-phenothiazyl) propanol**

A solution of the compound XIII (11.85 g) in dry diethyl ether (33 ml) was added dropwise to a suspension of  $\text{LiAlH}_4$  (4.74 g) in dry diethyl ether (70 ml) and stirred overnight at room temperature. Excess  $\text{LiAlH}_4$  was decomposed by the dropwise addition of water and filtered. Removal of the solvent under reduced pressure gave the green solid XIV, (5.57 g, 54.7%).

**XV:  $\beta$ -(10-phenothiazyl) propoxy phosphonic acid dichloride**

A solution of XIV (1.0 g) and pyridine (1.0 ml) in dry chloroform (60 ml) was cooled to  $-15^\circ\text{C}$ . A solution of phosphorous oxychloride (4.73 ml) and pyridine (1.0 ml) and dry chloroform (40 mls) was added dropwise over 0.5 h. The reaction mixture was stirred at  $-15^\circ\text{C}$  for 2 h and the resulting homogeneous solution allowed to reach ambient temperature over 1.5 h. The chloroform was removed under reduced pressure and the crude product washed with toluene (3 x 50 ml) to remove any unreacted phosphorous oxychloride affording a green oil XV, (0.9 g, 65.2%).

**VIII:  $\beta$ -(10-phenothiazyl) propoxy phosphonic acid**

A solution of XV (0.9 g) in deionised water (60 ml) was stirred overnight. The crude product was extracted in

ethyl acetate (4 x 50 ml), washed with water, dried over sodium sulphate. The white crystals that formed were removed by filtration and the filtrate recrystallized a further 3 times to yield the product  
5 VIII, (0.301 g, 40%).

Calculated for VIII ( $C_{15}H_{16}O_4NSP$ ): C, 53.43; H, 4.76; N, 4.15; P, 9.19. Found: C, 63.58; H, 5.42; N, 4.77; P, 1.86.  $^1H$  NMR ( $CDCl_3$ ):  $\delta$  2.24-2.28 (t 2H,  $J=6.3$  Hz);  
10  $\delta$  3.67-3.70 (t, 2H,  $J=6.2$  Hz);  $\delta$  4.09-4.12 (t, 2H,  $J=6.5$  Hz);  $\delta$  6.91-7.19 (m, 8H).  $^{31}P$  NMR ( $CDCl_3$ ):  
 $\delta$  1.69-1.89 ( $H_3PO_4$ );  $\delta$  -11.96

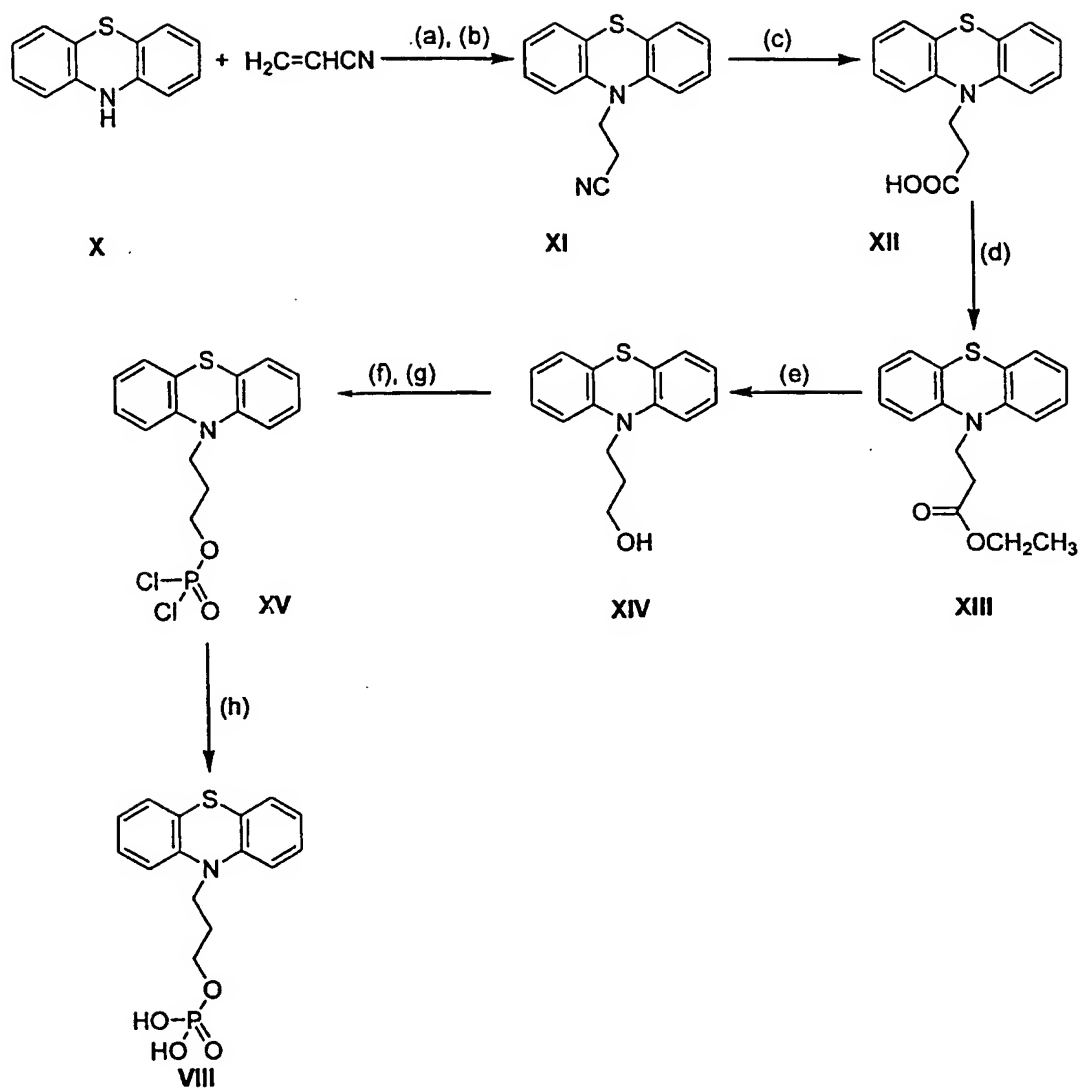
(f) nanostructured  $SnO_2:Sb$  films, prepared as  
15 described above, were modified by chemisorption of a monolayer of the p-type redox promoter VIII, also prepared as described above, from a chloroformic solution ( $0.02 \text{ mol dm}^{-3}$ ) during 6 h, washed with distilled isopropanol, dried in air and stored in a  
20 darkened vacuum desiccator for 24 h prior to use.

(g) A cell, with an internal spacing of about 400  $\mu m$ , was constructed from a modified  $TiO_2$  film and a modified  $SnO_2:Sb$  film prepared above using a  
25 thermoplastic gasket (IPBOND 2025, supplied by Industria Plastica Monregalese). This gasket had an opening at one corner.

(h) The sandwich structure was evacuated in a modified  
30 vacuum desiccator, dipped with the opening in the electrolyte solution, and filled by admitting air into the vacuum desiccator. The electrolyte solution consisted of  $LiClO_4$  ( $0.02 \text{ mol dm}^{-3}$ ) in  $\gamma$ -butyrolactone. It should be noted that both the  $LiClO_4$  and

$\gamma$ -butyrolactone were carefully purified and rigorously dried prior to use. Finally, the cell was sealed using a UV-curable epoxy resin.

SCHEME 1



Reagents and conditions for synthesis for Scheme 1 (VIII):

- (a) Acrylonitrile, 40% aq. solution benzyl trimethylammonium hydroxide (Triton B), 0° C
- (b) Reflux 1 h
- (c) Methanolic sodium hydroxide, Reflux 15 h.
- (d) Ethanol, conc. H<sub>2</sub>SO<sub>4</sub>, Reflux overnight.
- (e) LiAlH<sub>4</sub>, Diethyl ether (dry)
- (f) Phosphorous oxychloride, stir, -15° C for 2 h
- (g) Stir for 1.5 h to bring to ambient temperature
- (h) H<sub>2</sub>O

EXAMPLE 2*(a) Switching Times of Electrochromic (EC) Window*

The rate of colouration of the 2.5 cm x 2.5 cm EC window assembled as described in Example 1 was measured following application of a voltage of 1.2 V which biased the viologen modified nanostructured  $\text{TiO}_2$  film negative of the phenothiazine modified  $\text{SnO}_2:\text{Sb}$  film. The colouration time, defined as the time taken for the transmittance to decrease by two-thirds of the difference between the steady-state transmittances in the bleached and coloured states, was about 450 ms. The rate of bleaching of the same EC window was measured by reversing the polarity of the voltage applied to the previously coloured device. The bleaching time, defined as the average time taken for the transmittance to increase by two-thirds of the difference between the steady-state transmittances in the coloured and bleached states, was about 250 ms.

20

The measured colouring and bleaching times are, as far as the inventors are aware, the fastest switching times reported for EC windows of this area.

25 *(b) Colouration Efficiency of EC Window*

The peak and steady state currents of the 2.5 cm x 2.5 cm EC window were also measured during colouring and bleaching. The peak and steady-state currents measured on colouring were approximately  $10 \text{ mA cm}^{-2}$  and approximately  $30 \text{ } \mu\text{A cm}^{-2}$ , respectively. The peak and steady-state currents measured on bleaching the same EC window were approximately  $16 \text{ mA cm}^{-2}$  and approximately  $1 \text{ } \mu\text{A cm}^{-2}$ , respectively. The colouration efficiency  $\text{CE}(\lambda)$  at 550 nm, defined by Equation (1), was

30

determined from the slope of the plot of the increase in absorbance  $\Delta A(\lambda)$  versus the charge accumulated in the device  $\Delta Q$ . The measured CE (550 nm) was approximately  $110 \text{ C}^{-1} \text{ cm}^2$ .

5

$$CE(\lambda) = \frac{\Delta A(\lambda)}{\Delta Q} \quad (1)$$

Both the above peak and steady-state currents are very low and suggest that the power consumption of the EC window will be low and that it should have a long-term memory.

Concerning power consumption, the 2.5 cm x 2.5 cm EC window prepared in Example 1 will have an associated steady-state current of approximately 30  $\mu\text{A}$  in the coloured state. This implies that the rate of charge consumption is approximately  $2.4 \times 10^{-3} \text{ Cs}^{-1}$  or approximately  $1.5 \times 10^{16} \text{ electrons s}^{-1}$ .

Concerning the long-term memory, if a voltage of 1.2 V is applied to the EC window for 60 s and the circuit opened, the EC window first colours and then bleaches on the time-scale of hours. More quantitatively, the absorbance of the EC window measured at 608 nm takes about 3 h to return to the initially measured value, while the time required for the minimum transmittance in the coloured state to increase by 5% is 600 s.

#### *(c) Stability of EC Window*

The stability of the 2.5 cm x 2.5 cm EC window prepared in Example 1 was tested under ambient conditions by subjecting it to 10,000 electrochromic cycles. Each electrochromic cycle consisted of applying a potential



of 1.2 V, which biases the viologen modified nanostructured TiO<sub>2</sub> electrode negative of the phenothiazine nanostructured SnO<sub>2</sub>:Sb electrode, for 15 s and applying a voltage of 0.00 V for 15 s. The parameters used to characterise cell performance were measured after 1, 10, 100, 1,000 and 10,000 electrochromic cycles and are summarised in Table 1.

TABLE 1: Stability of Window under Electrochromic Cycling

Number of Electrochromic Cycles	1	10	100	1,000	10,000
Transmittance in Bleached State (%)	64	61	67	57	64
Transmittance in Coloured State (%)	13	12	17	14	23
Colouring Time (ms)	460	443	605	448	422
Bleaching Time (ms)	245	270	215	265	212
Peak Colouring Current (mA cm <sup>-2</sup> )	10	12	7	12	9
Peak Bleaching Current (mA cm <sup>-2</sup> )	16	17	17	12	11
Steady-State Coloured Current (μA cm <sup>-2</sup> )	33	28	17	13	15
Steady-State Bleached Current (μA cm <sup>-2</sup> )	1	2	1	2	1
Colouration Efficiency (C <sup>-1</sup> cm <sup>2</sup> )	110	110	110	110	105

- (a) This test was performed under ambient conditions on a 2.5 cm x 2.5 cm device assembled as described in Example 1.
- 5 (b) Each electrochromic cycle involved applying a voltage of 1.2 V which biased the viologen modified nanostructured electrode negative of the phenothiazine modified electrode for 15 s and then applying a voltage of 0.0 V for 15 s.

10

Another aspect of the stability, is the period over which it is possible to maintain the EC window in a coloured state. This aspect of the stability was examined by applying a voltage of 1.2 V, which biases the viologen modified nanostructured TiO<sub>2</sub> electrode negative of the phenothiazine nanostructured SnO<sub>2</sub>:Sb electrode, and which causes the device to colour. This voltage was applied for 15 s and, having determined that the time required for the minimum transmittance to increase by 5% is 180 s, this potential was applied for 15 s every 180 s. This maintained the EC window in the coloured state throughout. It was found that there was no significant degradation after 500 h.

- 25 Generally, the findings summarised in Table 1 establish that a 2.5 cm x 2.5 cm EC window assembled as described in Example 1 is relatively stable under ambient laboratory conditions over 10,000 electrochromic cycles while the findings summarised above establish that the same window is stable in the coloured state for 500 h.
- 30

EXAMPLE 3

Preparation of  $\beta$ -(10-phenothiazyl) propyl-phosphonic acid (illustrated in Scheme 2)

5

Steps (i) - (v) of Scheme 2 are described in relation to Scheme 1 in Example 1(e).

XVa:  $\beta$ -(10-phenothiazyl) propyl-phosphonate

10  $\beta$ -(10-phenothiazyl) propyl chloride IX (5 g,  $1.8 \times 10^{-2}$  M) was refluxed in 5 equivalents of triethyl phosphite for 48 h. The unreacted triethyl phosphite was removed by vacuum distillation to yield the crude product XVa which was taken to the next step without further  
15 purification.

$^1\text{H}$  NMR (chloroform-d):  $\delta$  1.17-1.22 (t, 6H,  $J=7.1$  Hz),  
 $\delta$  1.79-1.92 (m, 2H),  $\delta$  2.03-2.13 (m, 2H),  $\delta$  3.92-4.14  
(m, 6H),  $\delta$  6.84-7.17 (m, 8H, aromatic)

20

XVI:  $\beta$ -(10-phenothiazyl) propyl phosphono-trimethyl silyl ester

To an ice cold solution of XVa (0.15 g,  $4 \times 10^{-4}$  M) in  
25  $\text{CHCl}_3$  (dry) was added a cold solution of bromo-trimethylsilane (0.18 g,  $1.2 \times 10^{-3}$  M) in  $\text{CHCl}_3$  (dry). The reaction mixture was stirred ( $0^\circ\text{C}$ , 1 h) and then at room temperature for 16 h. The solvent was removed under reduced pressure to yield the crude silyl ester  
30 XVI which was taken to the next step without further purification.

$^1\text{H}$  NMR (chloroform-d):  $\delta$  0.00-0.39 (s, 18H),  $\delta$  1.75-1.90 (m, 2H),  $\delta$  2.00-2.20 (m, 2H),  $\delta$  3.84 (m, 2H),  $\delta$  6.80-7.20 (m, 8H, aromatic)

5

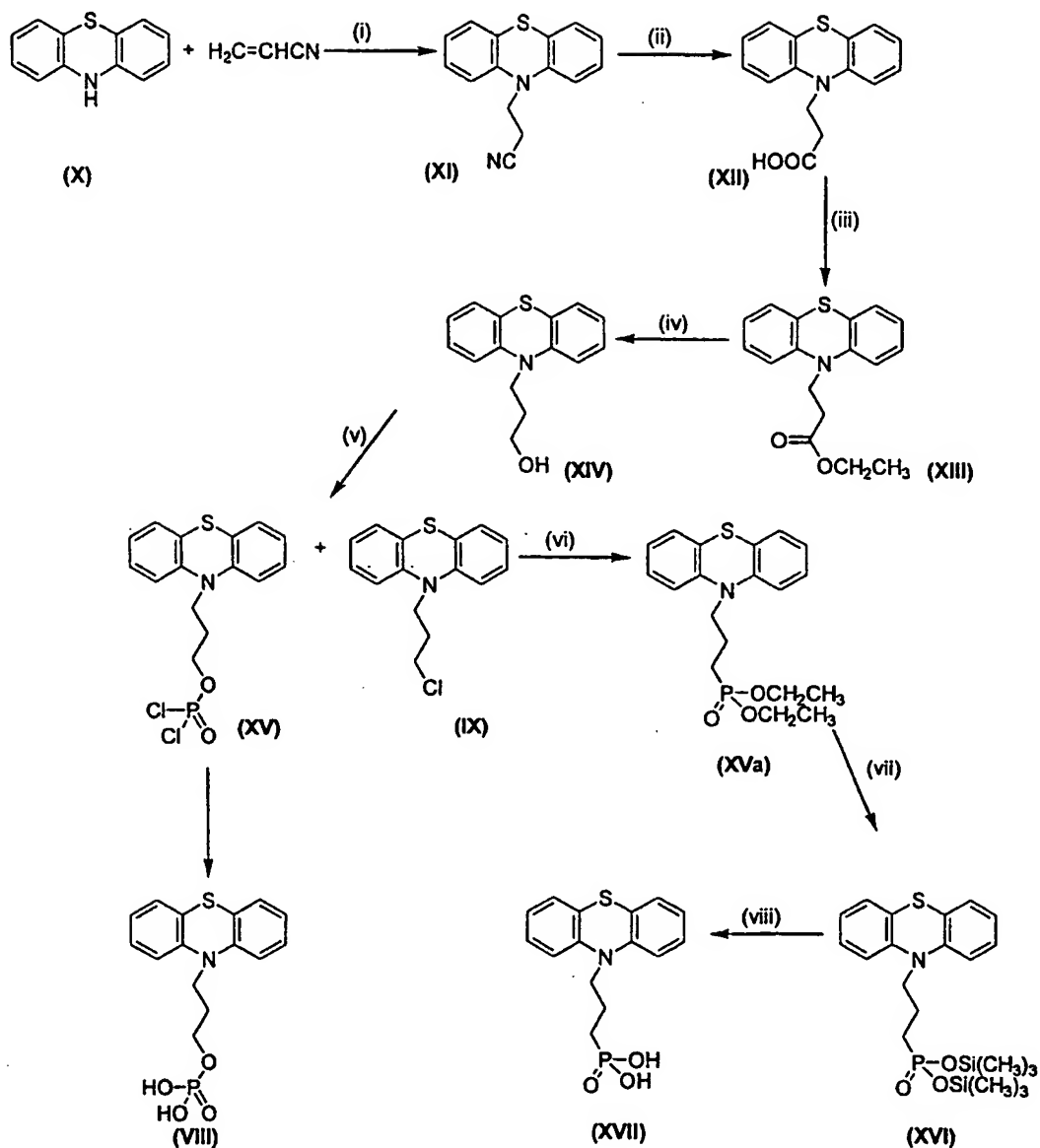
**XVII:**  $\beta$ -(10-phenothiazyl) propyl-phosphonic acid

**XVI** was stirred in a mixture of 1,4-dioxane:  $\text{H}_2\text{O}$  (1:1) at room temperature for 2h. The resulting precipitate  
10 was filtered and dried to yield the crude product **XVII**

$^1\text{H}$  NMR (methyl sulphoxide- $\text{d}_6$ ):  $\delta$  1.55-1.67 (m, 2H),  
 $\delta$  1.78-1.84 (t, 2H),  $\delta$  3.91-3.96 (t, 2H,  $J=7.0$  Hz),  
 $\delta$  6.8-7.3 (m, 8H, aromatic)

15

SCHEME 2



Reagents and conditions for synthesis for Scheme 2 (XVI):

- (i) acrylonitrile, Triton B (40% aq. solution),  $0^{\circ}\text{C}$ ; reflux 1 h
- (ii) methanolic sodium hydroxide, reflux 15 h;
- (iii) ethanol-toluene, conc.  $\text{H}_2\text{SO}_4$ , reflux 12 h;
- (iv) diethyl ether (dry),  $\text{LiAlH}_4$ ;
- (v) pyridine-chloroform (dry), phosphorous oxychloride, stir,  $-15^{\circ}\text{C}$ , 2 h; stir, RT, 1.5 h;
- (vi) triethyl phosphite, reflux, 48 h
- (vii) dry chloroform,  $0^{\circ}\text{C}$ ; bromotrimethyl silane, dry chloroform,  $0^{\circ}\text{C}$ ; stir, RT, 16 h
- (viii) 1,4-Dioxane/ $\text{H}_2\text{O}$  (1:1), stir, RT, 2 h.

EXAMPLE 4

Preparation of  $\beta$ -(10-phenothiazyl) propionate  
phosphonic acid (illustrated in Scheme 3)

5

XXVI:  $\beta$ -(10-phenothiazyl) propionitrile

To an ice cold solution of phenothiazine (XXV, 50g) in  
acrylonitrile (45 mL) was added Triton B (0.6 mL of a  
10 40% aq. soln.). After some time a vigorous reaction  
took place. The reaction mixture was heated on a steam  
bath for 2 h and allowed to cool. The resulting crude  
solid was crystallized from a 30:70 mixture of hot  
ethanol and acetone to yield orange crystals of XXVI.

15

XXVII:  $\beta$ -(10-phenothiazyl) propionic acid

The compound XXVI (20 g) was refluxed for 15 h in 450  
mL of methanolic sodium hydroxide (methanol:water,  
20 350:105 mL). The crude product was poured into ice  
water and acidified by the addition of sulfuric acid (2  
mol dm<sup>-3</sup>). The crude product was crystallized from  
ethanol to yield XXVII.

25 <sup>1</sup>H NMR (chloroform-d):  $\delta$  2.66-2.67 (t, 2H, J=7.9 Hz);  $\delta$   
4.04-4.09 (t, 2H, J=7.9 Hz);  $\delta$  6.76-7.05 (m, 8H,  
aromatic)

XXVIII:  $\beta$ -(10-phenothiazyl) propionic acid chloride

30

XXVII (1.0 g) was refluxed in 10 mL of oxazyl chloride

for 3 h. Removal of oxazyl chloride under low pressure afforded the crude acid chloride **XXVIII** which was taken for the next step without further purification.

- 5  $^1\text{H}$  NMR (chloroform-d):  $\delta$  3.40-3.45 (t, 2H,  $J=7.9$  Hz);  $\delta$  4.27-4.32 (t, 2H,  $J=7.9$  Hz);  $\delta$  6.87-7.25 (m, 8H, aromatic)

**XXIX**:  $\beta$ -(10-phenothiazyl) propionate phosphate ester

10

**XXVIII** (1.0 g) was dissolved in dry chloroform containing a small quantity of pyridine. Diethyl hydroxy methylphosphonate was added and the reaction mixture was stirred at room temperature overnight.

- 15 Removal of the solvent under reduced pressure yielded the crude product **XXIX** which was taken to the next step without further purification.

- $^1\text{H}$  NMR (chloroform-d):  $\delta$  1.32-1.37 (t, 2H,  $J=7.9$  Hz);  $\delta$  2.93-2.98 (t, 2H,  $J=7.9$  Hz);  $\delta$  4.12-4.28 (m, 6H,  $J=7.9$  Hz);  $\delta$  4.41-4.44 (d, 2H,  $J=7.9$  Hz);  $\delta$  6.89-7.22 (m, 8H, aromatic)
- 20

- XXX**:  $\beta$ -(10-phenothiazyl) propionate phosphono-  
25 trimethyl silyl ester

- To an ice cold solution of **XXIX** (1.0 g,) in  $\text{CHCl}_3$  (dry) was added a cold solution of bromo-trimethylsilane (0.18 g,  $1.2 \times 10^{-3}$  M) in  $\text{CHCl}_3$  (dry). The reaction mixture was stirred (0 °C, 1 h) and then at room temperature for 16 h. The solvent was removed under reduced pressure to yield the crude silyl ester **XXX**
- 30

which was taken to the next step without further purification.

$^1\text{H}$  NMR (chloroform- $d$ ):  $\delta$  0.00 (s, 18H);  $\delta$  2.93-2.98  
5 (m, 2H);  $\delta$  4.23-4.26 (m, 4H,  $J=7.9$  Hz);  $\delta$  7.11-7.19  
(m, 8H, aromatic)

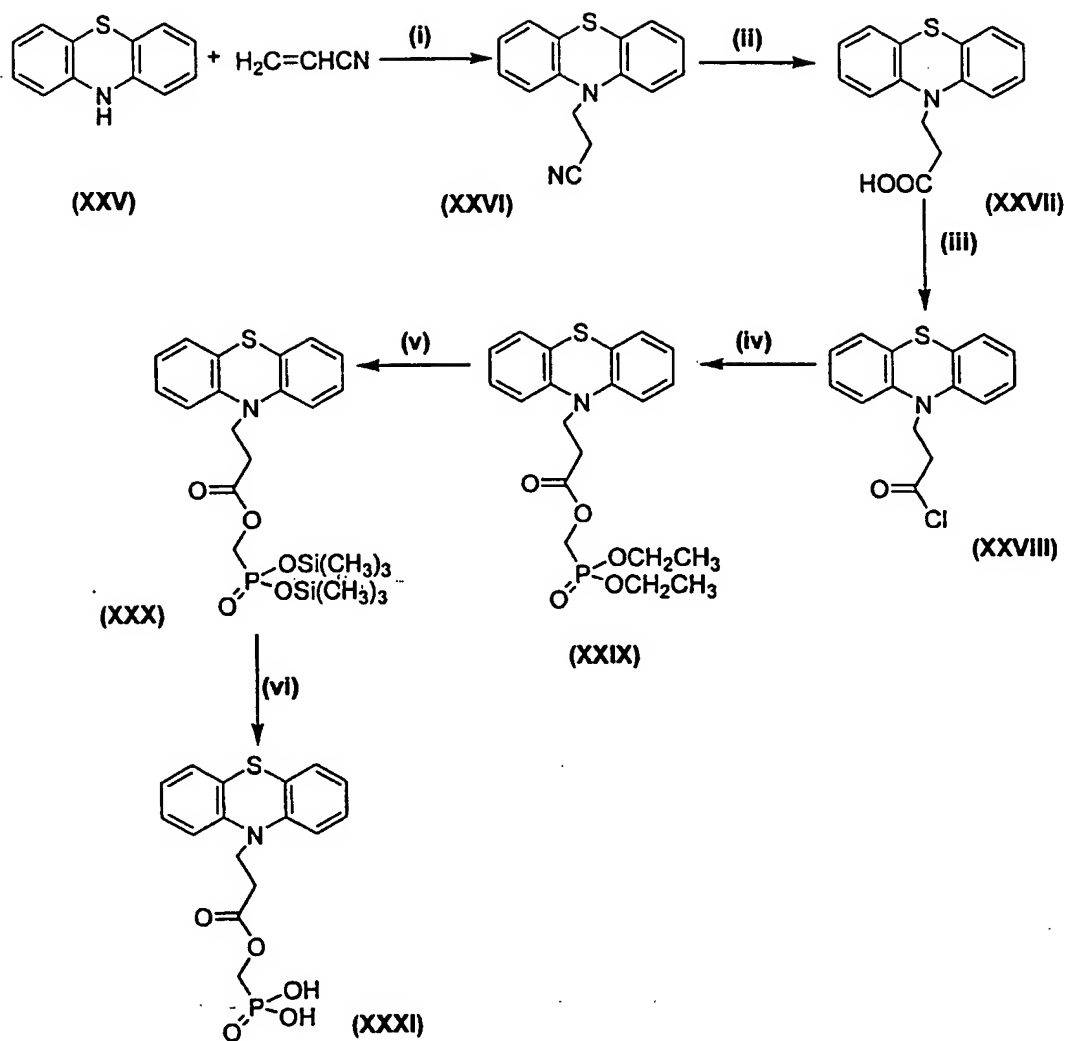
**XXXI:**  $\beta$ -(10-phenothiazyl) propionate phosphonic acid

10 **XXX** (0.1 g) was stirred in a mixture of 1,4-dioxane:  
 $\text{H}_2\text{O}$  (1:1) at room temperature for 2h. The resulting  
precipitate was filtered and dried to yield the crude  
product **XXXI**.

15  $^1\text{H}$  NMR (methyl sulphoxide- $d_6$ ):  $\delta$  2.93-2.98 (m, 2H);  
 $\delta$  4.23-4.26 (m, 4H);  $\delta$  7.11-7.19 (m, 8H, aromatic)



SCHEME 3



## Reagents and Conditions

(i) Triton B,  $0^\circ\text{C}$ , 2h; reflux 2h(ii) NaOH,  $\text{CH}_3\text{OH}$ , reflux 15h

(iii) Oxazyl chloride, reflux 3h

(iv) Diethyl hydroxy methylphosphonate, dry  $\text{CHCl}_3$ / Pyridine, stir r.t.(v) Bromotrimethylsilane, dry  $\text{CHCl}_3$ ,  $0^\circ\text{C}$ , stir r.t. 16h(vi) 1,4-Dioxane/  $\text{H}_2\text{O}$  (1:1), stir r.t. 2h

**EXAMPLE 5**

**Preparation of (1-Ferrocenyl) imido-benzylmethyl  
phosphonic acid (illustrated in Scheme 4)**

5

**XXXII: (1-Ferrocenyl) imino-benzyl-diethylphosphonate**

Ferrocene aldehyde (2.5 g,  $1.1 \times 10^{-2}$  M) was dissolved  
in toluene (80 mL). 4-amino benzyl phosphonate (2.6 g,  
10  $1.2 \times 10^{-2}$  M) and a catalytic amount of para-toluene  
sulphonic acid (0.13 g) was added and the reaction  
mixture was refluxed for 3 h, in a Dean-Stark setup.  
The solvent was concentrated under reduced pressure, to  
yield the crude product **XXXII** which was taken through  
15 to the next step without further purification.

$^1\text{H}$  NMR (chloroform-d): d 1.25-1.3 (t, 6H,  $J=7.0$  Hz),  
d 3.13-3.20 (d, 2H,  $J=21$  Hz), d 3.98-4.09 (q, 4H,  $J=7.0$   
Hz), d 4.26-4.83 (m, 9H), d 7.12-7.33 (dd, 4H,  
20 aromatic), d 8.35 (s, 1H)

**XXXIII: (1-Ferrocenyl) imido-benzyl-diethylphosphonate**

To a warm ( $50^\circ\text{C}$ ) solution of **XXXII** (5.39 g,  $1.2 \times 10^{-2}$   
25 M) in methanol (80 mL) was added solid  $\text{NaBH}_4$  (0.5 g,  
 $1.2 \times 10^{-2}$  M). A vigorous reaction occurred and the  
reaction mixture was refluxed for 3 h. The reaction  
mixture was cooled to room temperature stirred for 16  
h. The solvent was removed under reduced pressure, and  
30 the crude product was taken up in chloroform (4 x 50  
mL) and dried. The chloroform layer was washed with  
water and dried. Removal of the solvent afforded the  
crude product which was purified using column

chromatography (100% CHCl<sub>3</sub>) to yield XXXIII.

<sup>1</sup>H NMR (chloroform-d): d 1.25-1.30 (t, 6H, J=7.0 Hz),  
d 3.04-3.11 (d, 2H, J=21 Hz), d 3.99-4.05 (q, 4 H,  
5 J=7.0 Hz), d 4.05-4.26 (m, 11H), d 6.62-6.65 (d, 2H,  
aromatic), d 7.13-7.16 (d, 2H, aromatic)

**XXXIV:** (1-Ferrocenyl) imido-benzyl-diethyl  
trimethylsilyl ester

10

To an ice cold solution of XXXIII (1.0 g,  $2 \times 10^{-3}$  M)  
in CHCl<sub>3</sub> (dry, 10 mL) was added a cold solution of  
bromo-trimethylsilane (2.0 g,  $1.3 \times 10^{-2}$  M) in CHCl<sub>3</sub>  
(dry, 4 mL). The reaction mixture was stirred (0 °C, 1  
15 h) and then at room temperature for 16 h. The solvent  
was removed under reduced pressure to yield the crude  
silyl ester XXXIV which was taken to the next step  
without further purification.

20 <sup>1</sup>H NMR (chloroform-d): d 0.00 (s, 18H), d 2.94 (d, 2H,  
J=21 Hz), d 4.17-4.19 (m, 11H), d 6.79-6.85 (d, 2H,  
aromatic), d 7.09-7.20 (d, 2H, aromatic)

**XXXV:** (1-Ferrocenyl) imido-benzylmethyl phosphonic acid

25

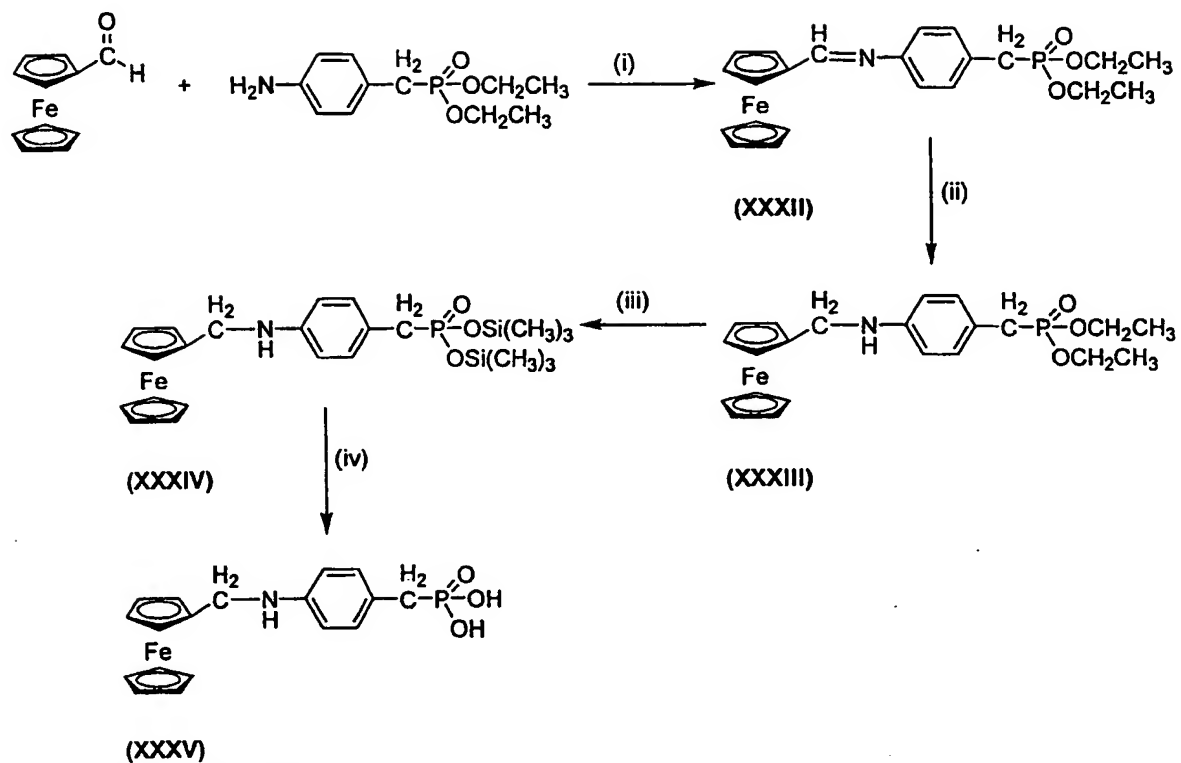
XXXIV was stirred in a mixture of DMF/ H<sub>2</sub>O (1:1) at  
room temperature for 4 h. The crude product that  
precipitated was filtered, washed with H<sub>2</sub>O and dried  
under vacuum to yield XXXV.

30

<sup>1</sup>H NMR (methyl sulphoxide-d<sub>6</sub>): d 2.71-2.78 (d, 2H, J=21  
Hz), d 3.93-4.26 (m, 11H), d 6.53-6.55 (d, 2H, J=7.9  
Hz), d 6.92-6.95 (d, 2H, J=7.1 Hz)

$^{31}\text{P}$  NMR (methyl sulphoxide- $\text{d}_6$ ): d 24.4

SCHEME 4



## Reagents and Conditions

- (i) Toluene, para-toluene sulphonic acid, reflux 4h
- (ii) Sodium Borohydride,  $\text{CH}_3\text{OH}$ , reflux 3h
- (iii) Bromotrimethylsilane, dry  $\text{CHCl}_3$ ,  $0^\circ\text{C}$ , 0.5h; r.t. 12h
- (iv) Dimethylformamide/  $\text{H}_2\text{O}$  (1:1), r.t. 4h

EXAMPLE 6

Preparation of  $\beta$ -(10-phenoxazyl) propionate phosphonic acid (illustrated in Scheme 5)

5

XIX:  $\beta$ -(10-phenoxazyl) propionitrile

To an ice cold solution of phenoxazine (XVII, 50g) in acrylonitrile (45 mL) was added Triton B (0.6 mL of a 40% aq. soln.). After some time a vigorous reaction took place. The reaction mixture was heated on a steam bath for 2 h and allowed to cool. The resulting crude solid was crystallized from a 30:70 mixture of hot ethanol and acetone to yield orange crystals of XIX.

15

XX:  $\beta$ -(10-phenoxazyl) propionic acid

The compound XIX was refluxed for 15 h in 450 mL of methanolic sodium hydroxide (methanol:water, 350:105 mL). The crude product was poured into ice water and acidified by the addition of sulfuric acid (2 mol  $\text{dm}^{-3}$ ). The crude product was crystallized from ethanol to yield XX.

25  $^1\text{H}$  NMR (chloroform- $d$ ):  $\delta$  2.74-2.80 (t, 2H,  $J=7.9$  Hz);  $\delta$  3.90-3.96 (t, 2H,  $J=7.9$  Hz);  $\delta$  6.54-6.88 (m, 8H, aromatic)

XXI:  $\beta$ -(10-phenoxazyl) propionic acid chloride

30

XX (1.0 g) was refluxed in 10mL of oxazyl chloride for

3 h. Removal of oxazyl chloride under low pressure afforded the crude acid chloride **XXI** which was taken for the next step without further purification.

- 5  $^1\text{H}$  NMR (chloroform-d):  $\delta$  3.19-3.28 (t, 2H,  $J=7.9$  Hz);  
 $\delta$  3.90-3.99 (t, 2H,  $J=7.9$  Hz);  $\delta$  6.47-6.90 (m, 8H,  
aromatic)

**XXII**:  $\beta$ -(10-phenoxazyl) propionate phosphate ester

10

- XXI** (1.0 g) was dissolved in dry chloroform containing a small quantity of pyridine. Diethyl hydroxy methylphosphonate was added and the reaction mixture was stirred at room temperature overnight. Removal of  
15 the solvent under reduced pressure yielded the crude product **XXII** which was taken to the next step without further purification.

- $^1\text{H}$  NMR (chloroform-d):  $\delta$  1.35-1.42 (t, 6H,  $J=6.9$  Hz);  $\delta$   
20 2.77-2.82 (d, 2H,  $J=7.3$  Hz);  $\delta$  3.91-3.96 (d, 2H,  $J=7.6$   
Hz);  $\delta$  4.11-4.28 (m, 4H);  $\delta$  4.41-4.44 (d, 2H,  $J=8.8$  Hz),  
 $\delta$  6.55-6.87 (m, 8H, aromatic)

**XXIII**:  $\beta$ -(10-phenoxazyl) propionate phosphono-

- 25 trimethyl silyl ester

- To an ice cold solution of **XXII** (1.0 g,) in  $\text{CHCl}_3$  (dry) was added a cold solution of bromo-trimethylsilane (0.18 g,  $1.2 \times 10^{-3}$  M) in  $\text{CHCl}_3$  (dry). The reaction  
30 mixture was stirred ( $0^\circ\text{C}$ , 1 h) and then at room temperature for 16 h. The solvent was removed under

reduced pressure to yield the crude silyl ester **XXIII** which was taken to the next step without further purification.

- 5  $^1\text{H}$  NMR (chloroform- $d$ ):  $\delta$  0.0 (s, 18H);  $\delta$  2.65-2.70 (t, 2H,  $J=7.6$  Hz);  $\delta$  3.80-3.86 (m, 2H);  $\delta$  4.25-4.36 (t, 2H,  $J=10.0$  Hz);  $\delta$  6.44-6.80 (m, 8H, aromatic)

**XXIV**:  $\beta$ -(10-phenoxazyl) propionate phosphonic acid

10

**XXIII** (0.1 g) was stirred in a mixture of 1,4-dioxane:  $\text{H}_2\text{O}$  (1:1) at room temperature for 2h. The resulting precipitate was filtered and dried to yield the crude product **XXIV**.

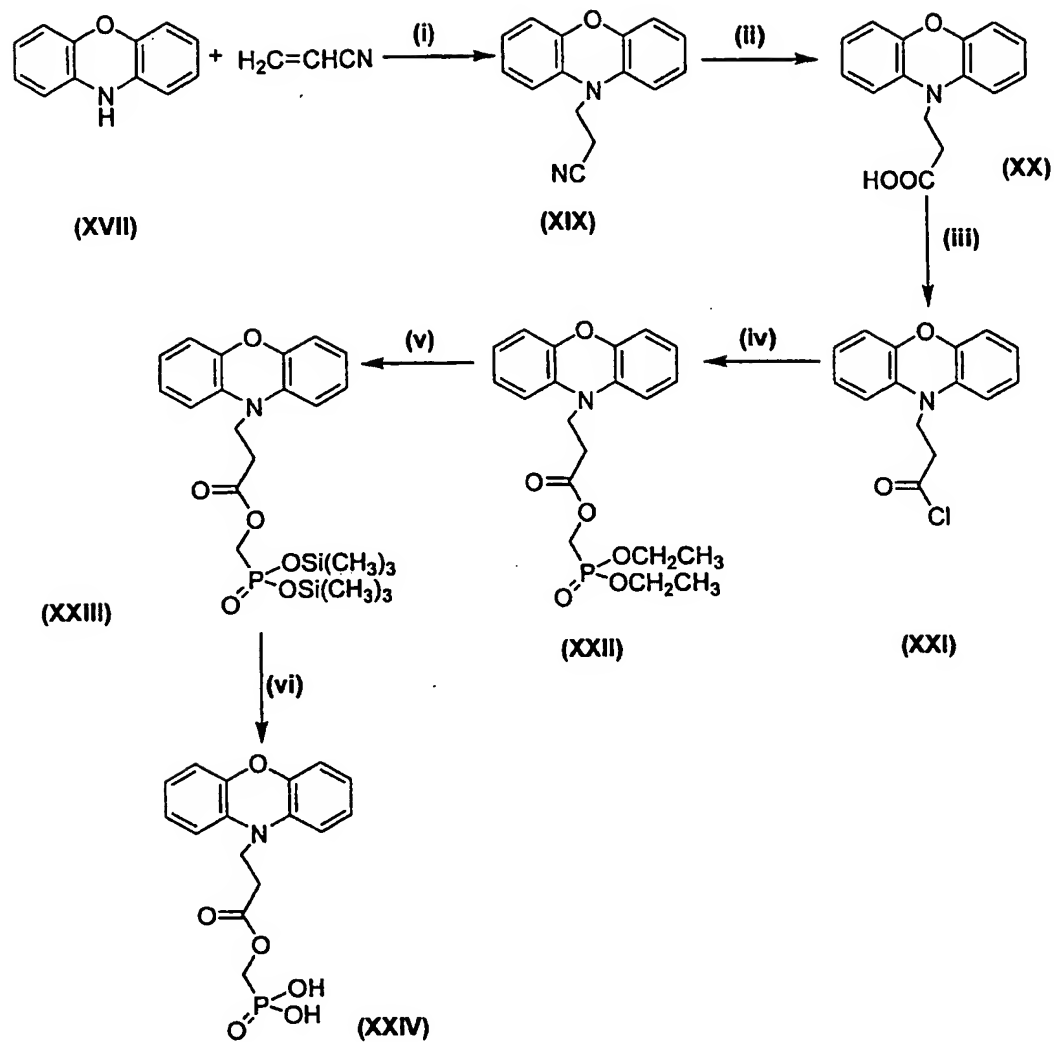
15

$^1\text{H}$  NMR (methyl sulphoxide- $d_6$ ):  $\delta$  2.60-2.67 (m, 4H),  $\delta$  3.66-4.20 (t, 2H,  $J=7.0$  Hz),  $\delta$  6.49-6.86 (m, 8H, aromatic)

- 20  $^{31}\text{P}$  NMR (methyl sulphoxide- $d_6$ ): 24.5



SCHEME 5



## Reagents and Conditions

(i) Triton B,  $0^\circ\text{C}$ , 2h; reflux 2h(ii) NaOH,  $\text{CH}_3\text{OH}$ , reflux 15h

(iii) Oxazyl chloride, reflux 3h

(iv) Diethyl hydroxy methylphosphonate, dry  $\text{CHCl}_3$ / Pyridine, stir r.t.(v) Bromotrimethylsilane, dry  $\text{CHCl}_3$ ,  $0^\circ\text{C}$ , stir r.t. 16h(vi) 1,4-Dioxane/  $\text{H}_2\text{O}$  (1:1), stir r.t. 2h

EXAMPLE 7Stability Tests5 *Preparation of Nanostructured Electrodes:*

All glass was thoroughly cleaned prior to use. Each sheet was manually cleaned using detergent which was thoroughly rinsed off using water. This was then  
10 washed with acetone to remove all water present and the acetone was evaporated using hot air. Each film was deposited using a doctor-blading technique. An adhesive stencil was placed over each glass electrode giving the required geometry necessary to leave a perimeter of 5  
15 mm. The glass surface was cleaned with iso-propanol and air-dried prior to deposition. A deposit of sol was placed at one end of the glass and manually drawn to the opposite end of the glass with a glass rod (7 mm diameter) leaving an even deposit of the sol. The  
20 cathode was a 50mm x 50mm square TEC 15 glass sheet with nanoporous nanocrystalline titanium dioxide (prepared as in Example 1 (a) except that the films were dried with hot air and sintered in air for 1 h) coated on an area of 40mm x 40mm square at the centre  
25 of the window, leaving an exposed one half centimetre perimeter for sealing materials. The anode was a 50mm x 50mm square TEC 15 glass sheet with nanoporous nanocrystalline antimony doped tin oxide (prepared as  
30 hot air and sintered for 1 h) coated on an area 40mm x 40mm square at the centre of the window, leaving an exposed one half centimetre perimeter for sealing materials.

### Modification of Nanostructured Electrodes

Prior to being modified with the redox compound, the nanostructured cathodes and anodes were placed in an oven at 350 °C to remove any water vapour or organic material. The electrodes were allowed to cool to approximately 80 °C before being placed into the redox compound solutions. All cathodes consisting of a nanostructured TiO<sub>2</sub> working electrode were modified by chemisorption of the viologen *bis*-(2-phosphonoethyl)-4,4'-bipyridinium dichloride from an aqueous solution (1 x 10<sup>-2</sup> mol dm<sup>-3</sup>) containing 0.1 M LiClO<sub>4</sub> over a 2 h period. Following the derivatisation process, each film was placed horizontally in a wash bath of ethanol for one minute. The washed, derivatised electrodes were dried using hot air.

All anodes consisting of antimony doped tin oxide electrodes were derivatised with a series of six redox promoters giving six sets of six windows as outlined below:

**Set A:** No redox promoter chemisorbed onto the antimony doped tin oxide electrodes

25

**Set B:** A solution of  $\beta$ -(10-phenoxazyl) propionate phosphonic acid as prepared in Example 6 (ca. 1 x 10<sup>-3</sup> M in acetonitrile and 6 x 10<sup>-3</sup> M LiPF<sub>6</sub>) were prepared and six windows were immersed for two hours in this solution.

30

**Set C:** A solution of  $\beta$ -(10-phenothiazyl) propoxy phosphonic acid as prepared in Example 1(e) (ca. 1 x 10<sup>-3</sup> M in acetonitrile and 6 x 10<sup>-3</sup> M LiPF<sub>6</sub>) was

prepared and six windows were immersed for two hours in this solution.

Set D: A solution of  $\beta$ -(10-phenothiazyl) propyl-

- 5    phosphonic acid as prepared in Example 3 (ca.  $1 \times 10^{-3}$  M in chloroform and  $6 \times 10^{-3}$  M  $\text{LiPF}_6$ ) was prepared and six windows were immersed for two hours in this solution.

- 10   Set E: A solution of  $\beta$ -(10-phenothiazyl) propionate phosphonic acid as prepared in Example 4 (ca.  $1 \times 10^{-3}$  M in chloroform/acetonitrile (4:1) and  $6 \times 10^{-3}$  M  $\text{LiPF}_6$ ) was prepared and six windows were immersed for two hours in this solution.

15

Set F: A solution of (1-ferrocenyl) imido-benzylmethyl phosphonic acid as prepared in Example 5 (ca.  $1 \times 10^{-3}$  M in 1:1 chloroform:dimethyl sulfoxide and  $6 \times 10^{-3}$  M  $\text{LiPF}_6$ ) was prepared and six windows were immersed for

20   two hours in this solution.

- Following the derivatisation process, each film was placed horizontally in a wash bath of the respective solvent it was modified from, for one minute. The
- 25   washed, derivatised electrodes were dried using hot air. The windows were sealed immediately after drying. The cathode and anode were sandwiched together with the electrodes placed in an offset configuration with 2-3 mm offset on two opposite sides to provide an area for
- 30   an external ohmic contact.

The switching times and stability of each device (A-F) were tested as described in Example 2. The results are shown in Tables 2-7. Optical absorption spectra were

recorded using a Hewlett-Packard 8452A diode array spectrophotometer. A Solartron SI 1287 potentiostat was used to record potential-current characteristics. All reported testing was done at room temperature.

TABLE 2

## Set A - No Redox Promoter

Number of Electrochromic Cycles	1	10	100	1000	3500	7000
Transmittance in Bleached State (%)	69	66	67	68	70	70
Transmittance in Coloured State (%)	33	31	34	38	46	41
Steady-State Coloured Current ( $\mu\text{A cm}^{-2}$ )	290	330	300	290	270	250
Steady-State Coloured Current ( $\mu\text{A cm}^{-2}$ )	15	22	21	20	13	23
Colouring Time (ms)	500	500	400	300	300	400
Bleaching Time (ms)	800	800	500	600	300	400

TABLE 3

## Set No. B - Phenoxazine

Number of Electrochromic Cycles	1	10	100	1000	3500	7000
Transmittance in Bleached State (%)	67	67	67	69	69	69
Transmittance in Coloured State (%)	24	25	23	30	32	36
Steady-State Coloured Current ( $\mu\text{A cm}^{-2}$ )	550	2600	440	380	270	180
Steady-State Coloured Current ( $\mu\text{A cm}^{-2}$ )	12	10	16	12	4	10
Colouring Time (ms)	800	800	800	800	800	900
Bleaching Time (ms)	600	500	600	500	400	400

TABLE 4

## Set No. C - Phenothiazine (PPPA)

Number of Electrochromic Cycles	1	10	100	1000	3500	7000
Transmittance in Bleached State (%)	68	67	67	70	68	68
Transmittance in Coloured State (%)	36	35	35	51	44	46
Steady-State Coloured Current ( $\mu\text{A cm}^{-2}$ )	63	62	76	49	38	34
Steady-State Coloured Current ( $\mu\text{A cm}^{-2}$ )	11	29	29	12	7	-
Colouring Time (ms)	400	500	600	500	400	500
Bleaching Time (ms)	400	500	600	300	300	400



TABLE 5

## Set No. D - Alkyl Phenothiazine (PPP)

Number of Electrochromic Cycles	1	10	100	1000	3500	7000
Transmittance in Bleached State (%)	66	66	67	66	66	66
Transmittance in Coloured State (%)	18	18	20	21	24	26
Steady-State Coloured Current ( $\mu\text{A cm}^{-2}$ )	1060	990	860	610	390	320
Steady-State Coloured Current ( $\mu\text{A cm}^{-2}$ )	10	-	11	12	15	9
Colouring Times (ms)	1200	1200	1300	1300	1300	1200
Bleaching Times (ms)	500	500	400	500	500	400

TABLE 6

## Set No. E - Phenothiazine Ester (PPPE)

Number of Electrochromic Cycles	1	10	100	1000	3500	7000
Transmittance in Bleached State (%)	68	68	67	67	67	68
Transmittance in Coloured State (%)	20	18	17	17	18	18
Steady-State Coloured Current ( $\mu\text{A cm}^{-2}$ )	1780	1750	1700	1600	1490	1390
Steady-State Coloured Current ( $\mu\text{A cm}^{-2}$ )	5	9	4	11	13	8
Colouring Times (ms)	1000	1400	900	800	1000	1000
Bleaching Times (ms)	500	500	600	500	500	500

TABLE 7

## Set No. F - Ferrocene (Fc)

Number of Electrochromic Cycles	1	10	100	1000	3500	7000
Transmittance in Bleached State (%)	57	58	58	58	60	61
Transmittance in Coloured State (%)	16	13	13	15	21	21
Steady-State Coloured Current ( $\mu\text{A cm}^{-2}$ )	470	-	270	-	130	100
Steady-State Coloured Current ( $\mu\text{A cm}^{-2}$ )	11	10	7	9	6	6
Colouring Times (ms)	1000	1400	900	800	1000	1000
Bleaching Times (ms)	500	500	600	500	500	500

The tabulated results can be explained as follows:

Transmittance in the bleached state (%) - the  
percentage of light passing through the device in the  
5 colourless state.

Transmittance in the coloured state (%) - the  
percentage of light passing through the device in the  
coloured state.

10

Steady State Current (SSC) - the value of the current  
when it has reached an equilibrium.

Generally, the findings summarised for A-F in Tables 2-  
15 7 establish that a 40 x 40 mm EC window assembled as  
described above is stable under ambient laboratory  
conditions over 7000 electrochromic cycles. The values  
of the transmittance in the colourless state are  
generally consistent throughout each test indicating  
20 that a large proportion of the incident light is  
passing through each device even after 7000 cycles.  
This indicates substantially no optical degradation of  
the films. The transmittance values in the coloured  
state are also generally consistent. The dynamic  
25 ranges between the transmittance in the colourless  
state and the transmittance in the coloured state are  
large which indicate good performance for an EC device.  
The SSC values for the coloured state are generally  
less than 25 micro amps  $\text{cm}^{-2}$ . This indicates a very  
30 small leakage current. The SSC for the bleached state  
in each case is of the order of 1 micro amp  $\text{cm}^{-2}$ .  
These low power consumption readings illustrate the  
memory effect of the devices as constructed.  
Furthermore, each device exhibits rapid switching times

for both the coloured and colourless states. Colouring times range from 30 to 75 ms/cm<sup>2</sup> and bleaching times from 25 to 50 ms/cm<sup>2</sup>. These times are significantly faster than those obtained with conventional devices

5 which have switching times of at least 1 s/cm<sup>2</sup>.

The advantages of the EC devices of the invention over previous EC devices are:

- 10
1. They are fast switching.
  2. They provide deeper colouration.
  3. The range of colours is greater.
  4. They have low steady state current.

## CLAIMS

1. A nanoporous, nanocrystalline film comprising a  
conducting metal oxide having an electroactive compound  
5 which is either a p-type or n-type redox promoter or p-  
type or n-type redox chromophore adsorbed thereto.

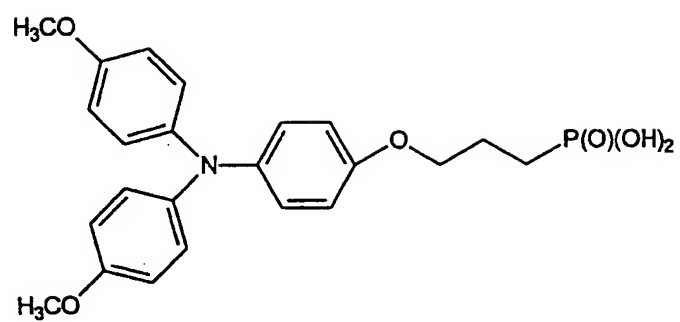
2. A film according to claim 1, wherein the  
conducting metal oxide is selected from any of the  
10 following:

- (a)  $\text{SnO}_2$  doped with F, Cl, Sb, P, As or B;
- (b)  $\text{ZnO}$  doped with Al, In, Ga, B, F, Si, Ge,  
Ti, Zr or Hf;
- 15 (c)  $\text{In}_2\text{O}_3$  doped with Sn;
- (d)  $\text{CdO}$
- (e) Ternary oxides such as  $\text{ZnSnO}_3$ ,  $\text{Zn}_2\text{In}_2\text{O}_5$ ,  
 $\text{In}_4\text{Sn}_3\text{O}_{12}$ ,  $\text{GaInO}_3$  or  $\text{MgIn}_2\text{O}_4$ ;
- (f)  $\text{TiO}_2/\text{WO}_3$  or  $\text{TiO}_2/\text{MoO}_3$  systems; and
- 20 (h)  $\text{Fe}_2\text{O}_3$  doped with Sb;
- (g)  $\text{Fe}_2\text{O}_3/\text{Sb}$  or  $\text{SnO}_2/\text{Sb}$  systems.

3. A film according to claim 2 wherein the  
conducting metal oxide is  $\text{SnO}_2$  doped with Sb.  
25

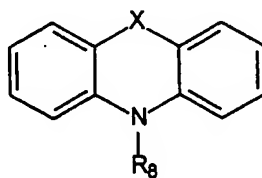
4. A film according to any of claims 1 to 3,  
wherein the electroactive compound is a p-type redox  
promoter or p-type redox chromophore.

30 5. A film according to claim 4, wherein the  
electroactive compound is selected from compounds of  
the following formulae IV - VII:

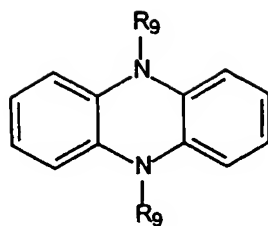


IV

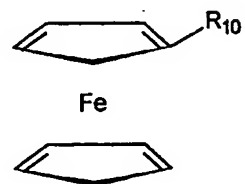
5



V

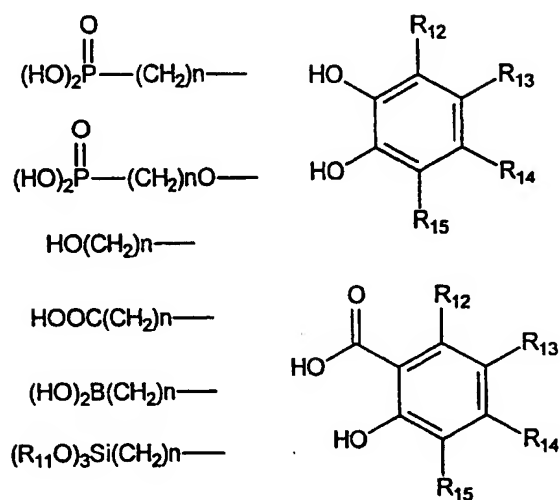


VI

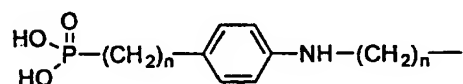
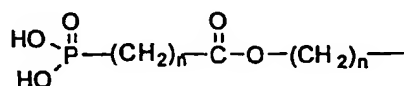


VII

wherein X in formula V is S or O and  $R_8$ - $R_{10}$  are each independently selected from the following:



5



10 wherein  $R_{11}$  is  $C_{1-10}$  alkyl and  $R_{12}$ - $R_{15}$  are each independently hydrogen;  $C_{1-10}$  alkyl;  $C_{1-10}$  alkylene; optionally substituted aryl; halogen; nitro; or an alcohol group; and  $n = 1-10$ .

15 6. A film according to claim 5, wherein the electroactive compound is selected from:

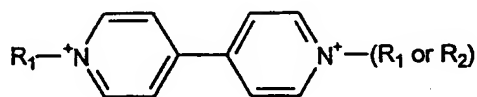
- (1)  $\beta$ -(10-phenothiazyl) propoxy phosphonic acid;
- (2)  $\beta$ -(10-phenothiazyl) propyl-phosphonic acid;
- 20 (3)  $\beta$ -(10-phenoxazyl) propionate phosphonic acid;



- (4)  $\beta$ -(10-phenothiazyl) propionate phosphonic acid;  
and  
(5). (1-ferrocenyl) imido-benzylmethyl phosphonic acid.

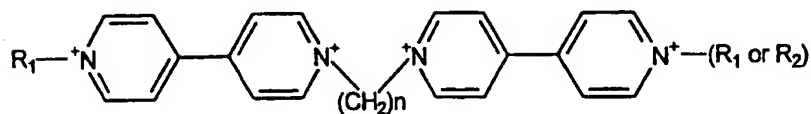
- 5 7. A film according to any of claims 1 to 3,  
wherein the electroactive compound is an n-type redox  
promoter or n-type redox chromophore, preferably an n-  
type redox chromophore selected from compounds of the  
following general formulae I-III:

10



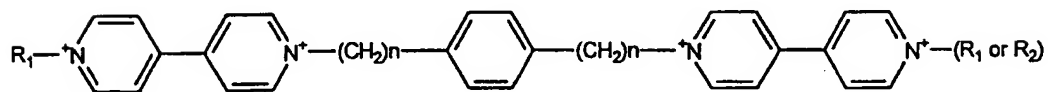
2X

I



4X

II

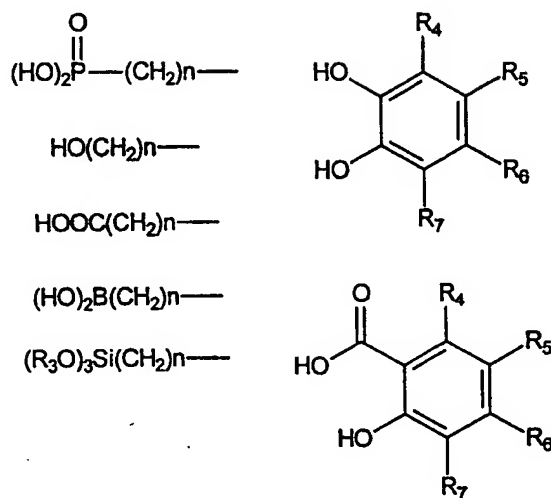


4X

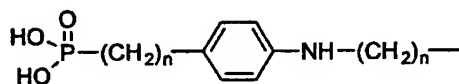
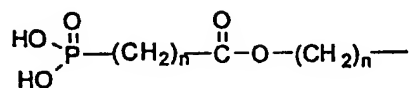
III

15

wherein  $R_1$  is selected from any of the following:



5



10

$R_2$  is selected from  $\text{C}_{1-10}$  alkyl, N-oxide, dimethylamino, acetonitrile, benzyl and phenyl optionally mono- or di-substituted by nitro;

15

$R_3$  is  $\text{C}_{1-10}$  alkyl and  $R_4$ - $R_7$  are each independently selected from hydrogen;  $\text{C}_{1-10}$  alkyl;  $\text{C}_{1-10}$  alkylene; aryl or substituted aryl; halogen; nitro; and an alcohol group;

20

X is a charge balancing ion which is preferably selected from chloride, bromide, iodide,  $\text{BF}_4^-$ ,  $\text{PF}_6^-$ , and  $\text{ClO}_4^-$ ; and  $n = 1-10$ ; especially

bis-(2-phosphonoethyl)-4,4'-  
bipyridinium dichloride.

8. Use of a film according to any of claims 1 to 7  
5 for the preparation of an electrode suitable for use in  
an electrochromic device.

9. An electrode for use in an electrochromic  
device comprising a transparent or translucent  
10 substrate bearing an electrically conducting coating  
which in turn bears a conducting nanostructured metal  
oxide film according to any of claims 1 to 7.

10. Use of an electrode according to claim 9 in the  
15 preparation of an electrochromic device.

11. An electrochromic device comprising at least  
one electrode according to claim 9.

20 12. An electrochromic device according to claim 11,  
comprising:

(a) a first electrode comprising a transparent or  
translucent substrate bearing an electrically  
25 conducting coating on its internal face which in turn  
bears a nanostructured film comprising a conducting or  
semiconducting metal oxide having an n-type or p-type  
redox chromophore or an n-type or p-type redox promoter  
adsorbed thereto, with the proviso that when the metal  
30 oxide is a semiconducting metal oxide, an n-type redox  
chromophore or promoter is adsorbed thereto;

(b) a second or counter electrode comprising a  
transparent or translucent substrate bearing an  
35 electrically conducting coating on its internal face

which in turn bears a nanostructured film comprising a conducting metal oxide having a p-type or n-type redox promoter or a p-type or n-type redox chromophore adsorbed thereto, with the proviso that when the first  
5 electrode comprises an n-type redox chromophore or promoter, the second electrode comprises a p-type redox promoter or chromophore or *vice versa*; and

(c) an electrolyte intermediate the electrodes.

10

13. An electrochromic device according to claim 12, wherein the nanostructured film of the first electrode comprises a semiconducting metal oxide having an n-type redox chromophore adsorbed thereto, and the second  
15 electrode comprises a conducting metal oxide having a p-type redox promoter adsorbed thereto.

14. An electrochromic device according to claim 12 or 13, wherein the semiconducting metal oxide is  
20 selected from oxides of titanium, zirconium, hafnium, chromium, molybdenum, tungsten, vanadium, niobium, tantalum, silver, zinc, strontium, iron ( $\text{Fe}^{2+}$  or  $\text{Fe}^{3+}$ ) or nickel or a perovskite thereof, preferably  $\text{TiO}_2$ ,  $\text{WO}_3$ ,  $\text{MoO}_3$ ,  $\text{ZnO}$  or  $\text{SnO}_2$ .

25

15. An electrochromic device according to any of claims 12 to 14, wherein the first electrode is the cathode and the nanostructured film coated thereon comprises  $\text{TiO}_2$  having an n-type redox chromophore of  
30 the formula I, II or III as defined in claim 7 adsorbed thereto; and the second electrode is the anode and the nanostructured film coated thereon comprises  $\text{SnO}_2:\text{Sb}$  having a p-type redox promoter of the formula IV, V, VI or VII as defined in claim 5 adsorbed thereto.

35

16. An electrochromic device comprising:

5 (a) a first electrode comprising a transparent or translucent substrate bearing an electrically conducting coating on its internal face which in turn bears a nanostructured film comprising a conducting or semiconducting metal oxide having an n-type or p-type redox chromophore adsorbed thereto, with the proviso  
10 that when the metal oxide is a semiconducting metal oxide, an n-type redox chromophore is adsorbed thereto;

(b) a second or counter electrode comprising a transparent or translucent substrate bearing an  
15 electrically conducting coating on its internal face which in turn bears a nanostructured film comprising a conducting metal oxide without an electroactive compound adsorbed thereto; and

20 (c) an electrolyte intermediate the electrodes.

17. An electrochromic device according to claim 16, wherein the nanostructured film of the first electrode comprises a semiconducting metal oxide having an n-type  
25 redox chromophore as defined in claim 7 adsorbed thereto.

18. An electrochromic device according to any of claims 12 to 17, wherein the electrodes are formed from  
30 a glass or plastics material, preferably glass coated with fluorine doped tin oxide or indium tin oxide.

19. An electrochromic device according to any of claims 12 to 18, wherein the electrodes are spaced

apart by a distance of up to 5 mm, preferably at a distance of from 50  $\mu$ m to 5 mm.

20. An electrochromic device according to any of  
5 claims 12 to 19, wherein the electrolyte is in liquid form and preferably comprises at least one electrochemically inert salt in solution in a solvent, especially lithium perchlorate in  $\gamma$ -butyrolactone.

10 21. A process for preparing an electrochromic device according to any of claims 12 to 20, which comprises:

(a) providing conducting and, if appropriate,  
15 semiconducting nanostructured metal oxide films;

(b) modifying the resulting films, if appropriate, by chemisorption of an electroactive compound of the p- or n-type;  
20

(c) applying the (modified) films to the internal face of the first and second electrodes; and

(d) adding an electrolyte so that it is disposed  
25 between the electrodes.

22. A process according to claim 21, wherein the conducting/semiconducting metal oxide films are treated by exposure to a water plasma stream prior to  
30 chemisorption of the electroactive compound.

23. Use of an electrochromic device according to any of claims 11 to 20 in electrochromic windows and displays.

24. A compound of any of the formulae V, VI or VII as defined in claim 5.

25. A compound according to claim 23 of the formula V which is selected from

- (1)  $\beta$ -(10-phenothiazyl) propoxy phosphonic acid;
- (2)  $\beta$ -(10-phenothiazyl) propyl-phosphonic acid;
- (3)  $\beta$ -(10-phenothiazyl) propionate phosphonic acid;
- and
- 10 (4)  $\beta$ -(10-phenoxazyl) propionate phosphonic acid.

26. A compound according to claim 24 of the formula VII which is (1-ferrocenyl) imido-benzylmethyl phosphonic acid.

15

27. Use of a compound according to any of claims 24 to 26 for the preparation of a film according to any of claims 1 to 7, or an electrode according to claim 9, or an electrochromic device according to any of claims 11 to 20.

20